Renewable and Sustainable Energy Reviews 21 (2013) 778–788

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Solar energy potentials in Iran: A review

Pouria Alamdari *, Omid Nematollahi, Ali Akbar Alemrajabi

Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

ARTICLE INFO

Article history:
Received 10 October 2012
Accepted 19 December 2012
Available online 1 March 2013

Keywords:
Solar energy
Horizontal radiation
Clearness index
GIS
Iran

ABSTRACT

In the present study, feasibility of using solar energy in different regions of Iran is investigated. For this purpose, maximum, minimum, and average values of annual horizontal radiation were calculated for sixty-three stations. Then, monthly and annual clearness indices and the annual average horizontal radiation map and GIS maps of horizontal radiation (GHR) were prepared for each month of the year. The results show that central and southern regions in Iran, except the coastal areas in the south, receive higher quantities of horizontal radiation. Among these regions, Southern Khorasan and Khuzestan provinces receive significant amounts of solar radiation such that the use of solar systems in these regions will be more economical. Delgan, Mahshahr, Shushtar, Abadeh, and Fadashk stations recorded an annual average horizontal radiation of above 500 W/m^2, which shows their potential for photovoltaic applications. These regions may be recommended for further study.

Contents

1. Introduction

Energy is known as the driving engine for economic development the world over. Global energy resources can be classified into the three main groups of fossil energies (oil, gas, coal, etc.), nuclear energy, and renewable energies (wind, solar, geothermal, hydropower, biomass, hydrogen, ocean, etc.). Industrial development and higher living standards have led to an increasing demand for energy, especially in the form of electrical energy. The global energy consumption is estimated to rise in 2035 to around 32.922 TW (about twice as much as its consumption in 2008) [1].

Given the limited sources of fossil fuels and nuclear energy and their rather rapid depletion, their replacement with new sources seems to be inevitable. Besides, fossil fuels are dangerously associated with carbon dioxide emissions that get trapped in the lower layers of the atmosphere and lead to extreme climate changes, floods, torrential rains, and droughts in many parts of the world [2].

Renewable energies eliminate the problems associated with fossil and nuclear energies such as pollution and environmental damages. Moreover, these resources are inexhaustible. Thus, they seem to be suitable alternatives to both fossil fuels and nuclear energy. Only of a recent origin, the technology to exploit these resources is nowadays growing rapidly. Sustainable development goals of the millennia in the energy sector and the need for enhanced energy security through recourse to different energy

* Corresponding author. Tel.: +98 3113915207.
E-mail address: p.alamdari@me.iut.ac.ir (P. Alamdari).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.12.052

resources are included among the main factors that have attracted immediate attention on a global scale to the development and advancement of renewable energies [3]. A dramatic increase is being currently witnessed in activities and investments by both public and private sectors in the research, development, and supply of new technologies in the field. It is as a result of such activities that the unit cost of power generation from renewable resources has remarkably decreased, making these resources more competitive than ever compared to conventional power generation systems.

Solar energy is a renewable energy which has attracted special attention in many countries. If only 0.1% of the solar energy incident on the earth can be converted to electrical energy at an efficiency rate of 10%, 3000 GW of power will be generated, which is by four times more than the energy consumed annually on a global scale [4]. In addition to the advantages of renewable energies mentioned above, the use of solar energy is additionally associated with greater benefits as follows:

1. Reclamation of degraded lands;
2. Reduced reliance on national power grid network;
3. Improved water quality across the nation; and
4. Acceleration in electrification of rural areas [5].

Iran is located in the Middle East and holds large reserves of oil and gas (9% of the global oil reserves and more than 15% of the global gas reserves) [6]. However, the domestic use of fossil fuels has increased dramatically due to its population explosion, industrial development, and higher living standards, a situation that may lead in the near future to its drastically reduced oil exports. Based on statistical report releases, Iran is among the top 20 countries in terms of greenhouse gas production. In 2008, the rate of carbon dioxide emission (in kilograms) to Gross Domestic Production (in US$) was 3.15, whereas the global average was 0.73. This is one major reason for turning to new sources of energy [7]. Although the use of renewable energies in Iran dates back to a decade ago, its full development and use are still in their embryonic stages [8].

Located between 25° and 40° north latitude, Iran is in a favorable position with respect to the potential amount of solar energy received. Solar radiation in Iran is estimated at about 1800 to 2200 $kW\,h/m^2$ per year, which is higher than the global average. An annual average of more than 280 sunny days is reportedly recorded over more than 90% of Iran's territorial land, which yields a highly significant potential source of energy. Thus, it is essential to estimate the exact amounts of radiation in different parts of Iran for designing optimum solar facilities.

The amount of radiation incidence on a point of Earth's surface depends on several factors, namely altitude, latitude, fraction of sunshine hours, relative humidity, precipitation, and air temperature. Several models have been developed to estimate the total amount of solar radiation on horizontal surfaces using various climatic parameters such as sunshine hours, cloudiness, relative humidity, minimum and maximum temperatures, wind speed, and so forth [9–11].

Wu et al. [12] used the Nanchang weather station (China) data from 1994 to 2005 to predict the daily total radiation by sunshine hours, ambient temperature, total precipitation, and dew point. Sen [13] proposed a nonlinear model to estimate the total solar radiation using the sunshine hours data available. Recently, Bulut and Buyukalaca [14] proposed a simple model to estimate the monthly average of daily total radiation on horizontal surfaces. The model is based on a sinusoidal function which only depends on a single parameter called 'the number of the year's day'. The model was able to estimate the monthly average values of daily total radiation in 68 provinces in Turkey with high accuracy. Paltridge and Proctor [15] used latitude and cloudiness to estimate direct and diffuse radiation. Fadare [16] used geographical and meteorological data from 195 cities in Nigeria over a ten-year period (1983 to 1993) to predict the solar potential energy using neural networks. In another study, Bakirci [17] investigated radiation estimating models associated with sunshine hours. Gastli and Charabi [18] predicted the solar energy potential for power generation in Oman using GIS maps. In their study, they first reviewed the methods developed for creating solar radiation maps using GIS tools and then developed Oman's solar radiation GIS maps for the months of January and July. They also used a number of methods to calculate the annual electrical energy generation potential. The results showed that the country had the potential to use solar energy all year long. Kelley et al. [19] investigated the feasibility of using solar energy for water transport. They proposed a method for calculating the feasibility of water transport by photovoltaic power systems based on the regional climate.

Investigating 16 different radiation models, Rehman [20] used altitude, latitude, and absorption coefficient to calculate the daily radiation in 41 cities in Saudi Arabia and compared the results. In another study, Al-Ayed et al. [21] proposed some empirical correlations and used one-year data (1986) to calculate the daily total, diffuse, and direct radiation quantities on horizontal surfaces in Riyadh. Several correlations among solar parameters have also been proposed by Benghanem and Joraid [22] to estimate the monthly average values of total and diffuse radiations in Medina. Sorapipatana [23] evaluated the potential for using solar energy in Thailand, using a satellite technique. The results showed that the average solar radiation largely depends on geographic features rather than on seasonal changes.

A number of studies have been conducted in Iran to estimate solar radiation. Using the model proposed by Paltridge and Proctor and one year data, Daneshyar [24] proposed a modified model for solar radiation in Tehran. Jafarpur and Yaghoubi [25] estimated monthly and annual radiation quantities in Shiraz. In another work, Samimi [26] proposed an altitude-dependent model using Meinel and Meinel model [27]. He used Sun–Earth correction, cloudiness coefficient, sunshine hours, and altitude to predict daily radiation in different parts of Iran. Following Samimi's work, Yaghubi and Sabzevari [28] used sunshine hours to calculate clearness index for Shiraz. In another study, Sabziparvar [29] selected the best model for Iran's coastal cities, using six solar radiation estimation models and compared the results with measured data. Sabziparvar and Shetaee [10] investigated six common models for estimating radiation in Iran's eastern and western arid and semiarid areas, and eventually proposed a new model for these areas. Their results showed that models based on cloudiness are capable of yielding more accurate estimations of radiation in Iran.

In the present study, the feasibility of exploiting solar energy in different parts of Iran is investigated. For this purpose and as the first step, average, maximum, and minimum values of solar radiation on a horizontal surface are calculated at different stations. Then, the monthly and average clearness indices are determined using the radiation data obtained from these stations and the average monthly summation of sunshine hours is calculated. Finally, GIS maps of average monthly and annual radiation are developed.

2. Iran

Iran (also known as Persia) is a vast country located in southwest Asia. Covering an area of 1648,195 km^2, it is the 18th

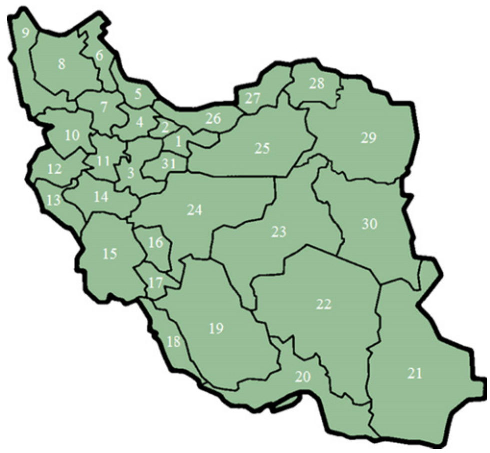

Fig. 1. Distribution map of Iran.

largest country in the world. It is limited by the republic of Azerbaijan, Armenia, Turkmenistan, and the Caspian Sea in the north; by Afghanistan and Pakistan in the east; by Iraq and Turkey in the west; and by the Gulf of Oman and the Persian Gulf in the south. Fig. 1 shows Iran's territorial divisions and Table 1 shows the names of the provinces according to Fig. 1.

Iran's climate is unique among its neighbors. Temperature differences between the warmest and the coldest regions are about 40° to 50 °C year around. While Shahrekord has a low of −30 °C on a winter night, Ahwaz experiences a summer high of +50 °C. In 2004 and 2005, Iran's Lut desert was the Earth's hottest spot.

In terms of rainfall, Iran belongs to the arid and semiarid climates influenced by the Siberian, Mediterranean, and Southern low pressure systems. Annual precipitation is highly variable ranging from over 2113 mm in the north to as low as 15 mm in desert areas [30].

Despite its climate diversity, most regions in the country, except for the northern coastal areas, receive high levels of solar radiation, as measured and recorded at different weather stations.

Table 1
Names of the provinces of Iran.

1. Tehran	12. Kermanshah	23. Yazd
2. Alborz	13. Ilam	24. Isfahan
3. Markazi	14. Lorestan	25. Semnan
4. Qazvin	15. Khuzestan	26. Mazandaran
5. Gilan	16. Chahar Mahaal and Bakhtiari	27. Golestan
6. Ardabil	17. Kohkiluyeh and Buyer Ahmad	28. North Khorasan
7. Zanjan	18. Bushehr	29. Razavi Khorasan
8. East Azarbaijan	19. Fars	30. South Khorasan
9. West Azarbaijan	20. Hormozgan	31. Qom
10. Kurdistan	21. Sistan and Baluchistan	
11. Hamadan	22. Kerman	

3. Weather data

Sixty three stations are uniformly distributed across the country for collecting and recording data at 10-min intervals. The amount of data collected (which comprise radiation and climatic parameters including temperature and wind direction) is large enough and the area covered is vast enough to yield reliable estimations of radiation in different regions. Table 2 presents the locations of the stations used in this study. The data required for the purposes of the present study were obtained

Table 2
Coordinates of some weather stations in Iran.

Site	Province	N (°)	E (°)	Site	Province	N (°)	E (°)
1. Meshkin Shahr	Ardabil	38.40	47.65	35. Rafsanjan	Kerman	30.32	56.22
2. Namin		38.37	48.37	36. Arzooye		28.43	56.37
3. Ahar	East-Azarbaijan	38.58	47.22	37. Shahre Babak		30.09	55.21
4. Bonab		37.40	46.02	38. Kish	Hormozgan	26.32	54.01
5. Mayan		38.08	46.04	39. Jask		25.66	57.72
6.Oscoo		37.91	46.14	40. Agh Ghala	Golestan	37.10	54.47
7. Chaldoran	West-Azarbaijan	39.05	44.45	41. Marave Tappe		37.89	55.71
8. Borojen	Isfahan	31.97	51.31	42. Behabad	Yazd	31.77	56.11
9. Moghar		33.57	52.18	43. Ardakan		32.59	54.26
10. Morche khort		33.10	51.47	44. Abarkuh		31.30	53.66
11. Varzaneh		32.46	52.61	45. Korit		33.48	56.94
12. Eshtehard	Tehran	35.72	50.37	46. Halvan		33.96	56.29
13. Rasul Abad	Hamedan	34.83	48.21	47. Delgan	Sistan and Baluchistan	27.48	59.45
14. Delvar	Bushehr	28.83	51.04	48. Dehak		27.17	62.55
15. Bardkhoon		27.98	51.49	49. Nosrat Abad		29.81	60.15
16. Esfarayen	North-Khorasan	37.08	57.50	50. Chabahar		25.29	60.63
17. Bojnurd		37.47	57.32	51. Khash		28.09	61.06
18. Davarzan	Razavi-Khorasan	36.26	56.81	52. Lutak		30.77	61.42
19. Sarakhs		36.31	61.14	53. Langarood	Gilan	37.25	50.23
20. Ghadamgah		36.05	59.00	54. Kahak	Semnan	35.14	52.32
21. Jangal		37.70	59.20	55. Moalleman		34.86	54.57
22. Rudab		35.61	57.30	56. Haddadeh		36.24	54.72
23. Afriz		34.44	58.96	57. Senar	Mazandaran	36.50	51.25
24. Khaf		34.58	60.16	58. Shurjeh	Ghazvin	35.96	48.33
25. Fadashk	South-Khorasan	32.78	58.78	59. Jarandagh		36.11	49.48
26. Nehbandan		31.56	60.07	60. Abadan	Khuzestan	30.35	48.29
27. Mahi Dasht	Kermanshah	34.26	46.79	61. Mahshahr		30.54	49.18
28. Divandare	Kordestan	35.97	47.04	62. Shushtar		32.04	48.85
30. Ghorveh		35.15	47.80	63. Hoseynie		32.21	48.40
31. Joyom	Fars	28.19	54.08	64. Soltanye	Zanjan	36.56	48.85
32. Marvdasht		29.98	52.92				
33. Abadeh		31.09	52.25				
34. Eghlid		30.88	52.61				

Table 3
Radiation values at the weather stations.

Site	Maximum irradiation (W/m^2)	Minimum irradiation (W/m^2)	Average irradiation (W/m^2)	Site	Maximum irradiation (W/m^2)	Minimum irradiation (W/m^2)	Average irradiation (W/m^2)
1. Meshkin Shahr	412	217	309	33. Eghlid	570	299	471
2. Namin	429	232	327	34. Rafsanjan	592	332	487
3. Ahar	450	252	336	35. Arzooye	534	380	472
4. Bonab	413	218	314	36. Shahre Babak	572	331	437
5. Mayan	536	282	402	37. Kish	519	317	450
6. Oscoo	505	320	404	38. Jask	548	341	464
7. Chaldoran	504	270	352	39. Agh Ghala	448	200	326
8. Borojen	592	342	481	40. Marave Tappe	465	240	333
9. Moghar	619	272	466	41. Behabad	617	292	481
10. Morche khort	465	220	331	42. Ardakan	561	281	453
11. Varzaneh	580	339	497	43. Abarkuh	568	318	468
12. Eshtehard	527	219	393	44. Korit	547	281	444
13. Rasul Abad	571	347	463	45. Halvan	559	297	422
14. Delvar	555	334	622	46. Delgan	646	408	519
15. Bardkhoon	533	296	415	47. Dehak	605	305	470
16. Esfarayen	570	273	439	48. Nosrat Abad	617	323	489
17. Bojnurd	555	238	407	49. Chabahar	500	288	416
18. Davarzan	559	262	420	50. Khash	615	387	493
19. Sarakhs	541	185	374	51. Lutak	594	355	487
20. Ghadamgah	593	195	410	52. Langarood	539	230	365
21. Jangal	610	301	480	53. Kahak	433	265	370
22. Rudab	567	264	434	54. Moalleman	570	297	469
23. Afriz	637	289	486	55. Haddadeh	562	264	456
24. Khaf	611	295	484	56. Senar	402	216	293
25. Fadashk	634	370	575	57. Shurjeh	574	290	416
26. Nehbandan	602	302	486	58. Jarandagh	570	294	418
27. Mahi Dasht	636	322	470	59. Abadan	564	251	453
28. Divan dare	567	325	447	60. Mahshahr	766	389	604
29. Ghorveh	546	239	403	61. Shushtar	664	418	537
30. Joyom	573	265	431	62. Hoseynie	540	224	376
31. Marvdasht	631	368	499	63. Soltanye	550	332	454
32. Abadeh	699	432	548				

from Iran's New Energies Organization (2007) (SUNA, being the acronym in Persian) [31].

The collected data were first organized and refined to eliminate possible errors. Data from weather stations were used to evaluate horizontal solar radiation (GHR) and sunshine hours. Table 3 shows the maximum, minimum, and average values of horizontal radiation (GHR) at each station. Clearly, Mahshahr in Khuzestan Province, with a horizontal radiation (GHR) of about 766 W/m^2 in June, ranks highest (GHR) among the stations investigated. Moreover, Sarakhs in Khorasan-e-Razavi Province has the minimum horizontal radiation, i.e., 185 W/m^2 in December. The average horizontal radiation (GHR) is 436 W/m^2.

Photovoltaic data and performance parameters under standard test conditions (STC) indicate that regions with a horizontal irradiation (GHI) of about 1000 W/m^2 should be regarded as economic zones for photovoltaic applications. The radiation required for a warranted photovoltaic region is 500 W/m^2 [32]. Delgan (in Sistan and Baluchistan Province), Mahshahr (in Khuzestan Province), Shushtar (in Khuzestan Province), Abadeh (in Fars Province) and Fadashk (in South-Khorasan Province) stations have average radiation values higher than the required minimum value, indicating that they are suitable sites that warrant further study for photovoltaic applications. Another characteristic of a suitable region for building photovoltaic facilities is locations with low differences between maximum and minimum values of horizontal radiation. In fact, when this difference decreases so that maximum and minimum values are close to the average value, average horizontal radiation may be taken as an appropriate estimation for the radiation in the region; hence, the maximum, minimum, and average values of horizontal radiation shown in Table 3.

4. Air clearness index

When solar radiation passes through the Earth's atmosphere, part of it is lost to absorption, reflection, and transmitting radiation diffusion. This attenuation is affected by moisture, dust, clouds or even temperature differences among atmospheric layers. Among all these, clouds play the most important role as radiation losses change with seasons due to seasonal changes in cloudiness. The changes may be expressed by the clearness Index ($\overline{K}_T$), which is defined as the global solar radiation on the surface of the earth divided by the extraterrestrial radiation at the top layer of the atmosphere. In other words, it is the proportion of the extraterrestrial solar radiation that makes it through to the surface, expressed by (1) below [33]:

$$\overline{K}_T = \frac{\overline{H}}{\overline{H_\circ}} \tag{1}$$

where, $\overline{K}_T$ is the monthly average of daily clearness Index, $\overline{H}$ is the monthly average of daily total radiation received by the horizontal plane on the Earth, and $\overline{H_\circ}$ is the radiation received by the same plane outside the Earth's atmosphere. Solar radiation intensity on a horizontal plane outside the Earth's atmosphere or on the Earth in the absence of the atmosphere may be obtained from the following equation:

$$G_{on} = G_{sc}\left[1+0.033\cos\left(\frac{360\times n}{365}\right)\right]\cos\theta_z \tag{2}$$

where, G_{sc} is the solar constant (G_{sc}=1367 W/m^2), n is the day of the year (e.g., for January 1st, n=1), and θ_z is the zenith angle (the angle between the vertical line and the sun's beam) obtained from

Table 4
Monthly clearness index for the weather station.

Site	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Province: Ardabil													
Meshkin Shahr	0.495	0.463	0.495	0.400	0.448	0.521	0.406	0.535	0.528	0.459	0.446	0.575	0.481
Namin	0.563	0.541	0.448	0.389	0.528	0.542	0.528	0.513	0.530	0.477	0.504	0.531	0.508
Province: East- Azarbaijan													
Ahar	0.577	0.555	0.436	0.338	0.375	0.448	0.502	0.594	0.601	0.734	0.636	0.624	0.535
Bonab	0.835	0.724	0.527	0.325	0.276	0.276	0.331	0.395	0.419	0.618	0.661	0.779	0.514
Oskoo	0.739	0.674	0.529	0.47895	0.513	0.536	0.640	0.661	0.722	0.648	0.649	0.802	0.633
Mayan	0.610	0.561	0.537	0.525	0.583	0.675	0.661	0.705	0.717	0.571	0.624	0.639	0.617
Province: West- Azarbaijan													
Chaldoran	0.712	0.656	0.476	0.407	0.420	0.524	0.486	0.669	0.634	0.527	0.607	0.631	0.562
Province: Isfahan													
Moghar	0.672	0.628	0.618	0.610	0.665	0.709	0.767	0.770	0.788	0.624	0.636	0.542	0.669
Morche Khort	0.457	0.457	0.416	0.369	0.512	0.501	0.481	0.589	0.538	0.472	0.461	0.433	0.474
Varzaneh	0.651	0.745	0.727	0.697	0.671	0.712	0.713	0.715	0.755	0.749	0.729	0.657	0.710
Borojen	0.726	0.750	0.642	0.600	0.637	0.722	0.729	0.715	0.747	0.666	0.604	0.686	0.685
Province: Tehran													
Eshtehard	0.554	0.601	0.599	0.534	0.562	0.611	0.563	0.680	0.639	0.626	0.421	0.588	0.582
Province: Hamedan													
Rasool Abad	0.675	0.626	0.693	0.650	0.653	0.678	0.710	0.732	0.714	0.636	0.701	0.715	0.682
Province: Bushehr													
Delvar	0.569	0.647	0.593	0.572	0.648	0.673	0.624	0.604	0.609	0.581	0.566	0.608	0.608
Bardkhoon	0.562	0.616	0.474	0.531	0.644	0.631	0.607	0.585	0.577	0.519	0.483	0.541	0.564
Province: North Khorasan													
Bojnoord	0.616	0.565	0.471	0.585	0.667	0.651	0.670	0.726	0.701	0.608	0.572	0.529	0.613
Esfarayen	0.654	0.602	0.555	0.625	0.708	0.693	0.720	0.726	0.698	0.707	0.661	0.599	0.662
Province: Razavi Khorasan													
Sarakhs	0.444	0.459	0.457	0.572	0.662	0.676	0.680	0.670	0.570	0.512	0.446	0.398	0.546
Khaf	0.634	0.590	0.785	0.737	0.709	0.706	0.761	0.770	0.762	0.732	0.649	0.604	0.703
Roodab	0.598	0.559	0.655	0.602	0.643	0.705	0.685	0.661	0.686	0.674	0.665	0.555	0.641
Afriz	0.719	0.620	0.595	0.698	0.744	0.740	0.774	0.814	0.806	0.703	0.667	0.590	0.706
Davarzan	0.618	0.587	0.567	0.628	0.702	0.679	0.702	0.724	0.594	0.578	0.510	0.580	0.622
Jangal	0.767	0.651	0.612	0.690	0.732	0.746	0.764	0.800	0.817	0.783	0.771	0.674	0.734
Ghadamgah	0.602	0.571	0.525	0.631	0.700	0.696	0.744	0.761	0.557	0.501	0.472	0.416	0.598
Province: South Khorasan													
Fadashk	0.693	0.595	0.584	0.694	0.746	0.750	0.783	0.798	0.825	0.803	0.758	0.735	0.730
Nehbandan	0.544	0.744	0.723	0.679	0.626	0.650	0.656	0.755	0.742	0.702	0.752	0.704	0.690
Province: Kermanshah													
Mahi Dasht	0.715	0.647	0.659	0.571	0.673	0.787	0.739	0.749	0.765	0.545	0.709	0.653	0.684
Province: Kordestan													
Divan Dare	0.747	0.730	0.629	0.570	0.605	0.707	0.698	0.686	0.769	0.561	0.653	0.692	0.671
Ghorveh	0.575	0.558	0.555	0.563	0.620	0.630	0.681	0.685	0.632	0.564	0.452	0.492	0.584
Province: Fars													
Joyom	0.662	0.656	0.631	0.648	0.693	0.666	0.524	0.518	0.539	0.535	0.496	0.466	0.586
Eghlid	0.741	0.700	0.683	0.683	0.664	0.696	0.679	0.564	0.709	0.676	0.516	0.635	0.662
Abadeh	0.772	0.777	0.738	0.666	0.664	0.724	0.857	0.801	0.853	0.840	0.801	0.810	0.775
Marvdasht	0.659	0.656	0.638	0.625	0.700	0.671	0.659	0.783	0.817	0.760	0.684	0.672	0.694
Province: Kerman													
Arzooye	0.641	0.598	0.593	0.642	0.646	0.585	0.598	0.632	0.666	0.772	0.722	0.722	0.651
Rafsanjan	0.663	0.655	0.631	0.666	0.698	0.671	0.714	0.736	0.737	0.713	0.638	0.611	0.678
Shahre Babak	0.578	0.566	0.528	0.573	0.610	0.573	0.566	0.579	0.753	0.731	0.645	0.627	0.611
Province: Hormozgan													
Jask	0.546	0.647	0.628	0.666	0.651	0.570	0.574	0.569	0.638	0.674	0.656	0.628	0.621
Kish	0.629	0.631	0.564	0.597	0.623	0.603	0.613	0.632	0.621	0.619	0.578	0.536	0.604
Province: Golestan													
Agh Ghala	0.564	0.433	0.424	0.441	0.489	0.492	0.471	0.584	0.577	0.513	0.507	0.440	0.495
Marave Tappe	0.560	0.504	0.442	0.383	0.527	0.511	0.491	0.611	0.567	0.514	0.517	0.541	0.514
Province: Yazd													
Abarkuh	0.650	0.642	0.636	0.631	0.680	0.695	0.690	0.697	0.712	0.655	0.602	0.599	0.657
Ardakan	0.671	0.641	0.619	0.604	0.659	0.670	0.693	0.693	0.626	0.677	0.664	0.547	0.647
Halvan	0.581	0.604	0.000	0.000	0.000	0.000	0.694	0.688	0.712	0.682	0.645	0.598	0.434
Korit	0.645	0.570	0.600	0.617	0.677	0.666	0.673	0.690	0.697	0.636	0.632	0.559	0.639
Behabad	0.693	0.620	0.605	0.659	0.694	0.666	0.713	0.774	0.777	0.702	0.690	0.557	0.679
Province: Sistan and Baluchistan													
Chabahar	0.504	0.537	0.521	0.590	0.599	0.575	0.601	0.502	0.523	0.656	0.529	0.477	0.551
Delgan	0.789	0.774	0.724	0.793	0.705	0.549	0.591	0.718	0.729	0.727	0.705	0.706	0.709

Table 4 (*continued*)

Site	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Dehak	0.580	0.572	0.579	0.603	0.587	0.731	0.693	0.679	0.692	0.688	0.662	0.525	0.633
Khash	0.721	0.696	0.696	0.757	0.616	0.527	0.596	0.620	0.765	0.765	0.705	0.679	0.679
Lutak	0.684	0.699	0.672	0.712	0.725	0.720	0.675	0.666	0.689	0.666	0.611	0.661	0.682
Nosrat Abad	0.663	0.610	0.597	0.638	0.711	0.658	0.737	0.765	0.753	0.727	0.663	0.588	0.676
Province: Gilan													
Langarood	0.626	0.501	0.519	0.614	0.682	0.576	0.626	0.609	0.380	0.430	0.459	0.570	0.549
Province: Semnan													
Haddadeh	0.689	0.649	0.680	0.658	0.698	0.683	0.706	0.718	0.731	0.670	0.720	0.567	0.681
Kahak	0.640	0.552	0.579	0.535	0.517	0.537	0.513	0.529	0.557	0.538	0.502	0.624	0.552
Moalleman	0.715	0.632	0.624	0.662	0.682	0.689	0.711	0.725	0.788	0.719	0.710	0.613	0.689
Province: Mazandaran													
Senar	0.537	0.459	0.411	0.397	0.506	0.459	0.384	0.382	0.400	0.464	0.507	0.467	0.448
Province: Ghazvin													
Shurje	0.641	0.577	0.599	0.489	0.608	0.636	0.677	0.742	0.675	0.629	0.559	0.643	0.623
Jarandagh	0.644	0.578	0.600	0.490	0.609	0.636	0.677	0.743	0.676	0.631	0.561	0.646	0.624
Province: Khuzestan													
Abadan	0.441	0.641	0.608	0.604	0.591	0.591	0.591	0.641	0.745	0.728	0.730	0.702	0.634
Hoseynieh	0.627	0.572	0.586	0.684	0.573	0.532	0.510	0.478	0.522	0.373	0.397	0.576	0.536
Mahshahr	0.686	0.869	0.917	0.884	0.893	0.934	0.881	0.904	0.750	0.709	0.856	0.792	0.840
Shushtar	0.789	0.663	0.794	0.728	0.732	0.813	0.784	0.800	0.747	0.749	0.756	0.835	0.766
Province: Zanjan													
Soltanyeh	0.733	0.694	0.63	0.603	0.674	0.649	0.682	0.708	0.740	0.621	0.690	0.699	0.677

the following equation:

$$\cos\theta_z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \quad (3)$$

where, ϕ is the location's latitude and δ is the tilt angle determined from the equation below:

$$\delta = 23.45\sin\left(360\frac{(284+n)}{365}\right) \quad (4)$$

in which, ω is the hour angle (equivalent to 15° per hour from the solar noon). Sunrise and sunset hour angles may be obtained from Eq. (3) with θ_z=90°:

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (5)$$

Day length is defined equivalent to twice the time interval from noon to sunset whose value is equal to:

$$t = \frac{2}{15}\omega_s \quad (6)$$

To determine the amount of daily radiation, Eq. (2) should be integrated from sunrise to sunset:

$$H_o = \frac{24}{\pi}G_{sc}\left[1+0.033\cos\left(\frac{360\times n}{365}\right)\right] \times\left[\cos\phi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\phi\sin\delta\right] \quad (7)$$

where, $H_\circ$ is in J/m^{2}day.

The monthly mean of daily extraterrestrial radiation, $\overline{H_\circ}$, can be calculated using Eq. (7) for the mean day of the month.

Table 4 shows monthly clearness indices for the weather stations investigated. The annual average of clearness index is presented in the last column in Table 4.

According to Table 4, Mahshahr station in Khuzestan Province has the highest clearness index of about 0.934 in June. On the other hand, Bonab station in East-Azarbaijan Province has the lowest monthly clearness index of about 0.276 in May. Based on the annual average clearness index, the maximum and minimum annual values for this parameter are 0.839 and 0.447 in Mahshahr and Senar (in Mazandaran Province) stations, respectively. The average clearness index for all stations in Iran is about 0.630.

5. The amount of sunshine hours

Field investigations are required to gain detailed information about solar radiation in a given region. A crucial parameter involved in identifying regions with the potential for installing solar equipment and power generators using solar energy is the sunshine hours, which is defined as the time during which the sun is visible [33]. The amount of daily sunshine hours at the study stations was measured using Campbell–Stokes sunshine recorders and reported as annual average of monthly sunshine hours in Fig. 2 for the regions studied.

Clearly, Arzooye station in Kerman Province had the highest annual average of total sunshine hours per month (about 285 h) while Bojnourd station in North-Khorasan Province had the lowest (only about 120 h). The annual average of total monthly sunshine hours in Iran was obtained to be about 250.79 h.

6. Solar radiation GIS maps

Maps have been used for thousands of years, but only within the last few decades have we witnessed an unprecedented development that combines mapping with computer graphics and databases to create Geographic Information Systems.

GIS uses layers, called "themes", to overlay different types of information, much as some static maps use Mylar overlays to add tiers of information to a geographic background. Each theme represents a category of information, such as roads or forest cover. As with the old Mylar maps, the layers which are underneath remain visible while additional themes are placed above. The themes in the above graphic are only a small example of the wide array of information that can be viewed or analyzed with a GIS.

GIS is all about spatial data and the tools for managing, compiling, and analyzing that data. Elevation, temperature, and contamination concentrations are the types of data that can be represented in GIS maps. Each raster cell represents a measurement such as a cell's relationship to a fixed point or a specific concentration level. Because obtaining values for each cell in a raster is typically not practical, sample points are used to derive

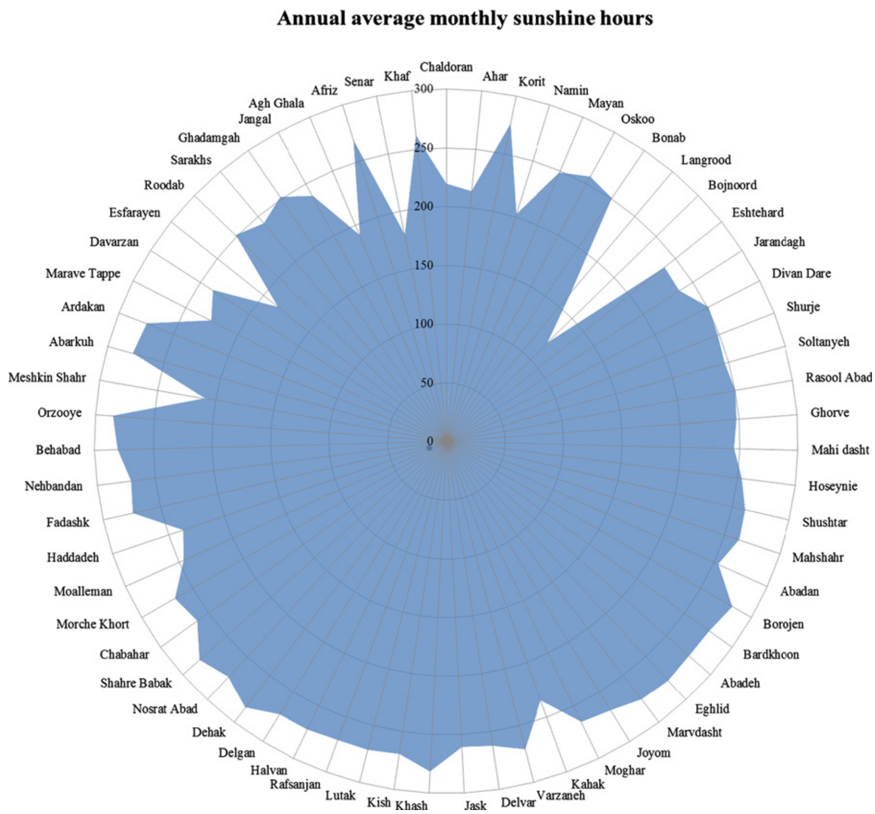

Fig. 2. The annual average of monthly sunshine hours.

the intervening values using the interpolation tools in ArcGIS Spatial Analyst. Therefore, the ArcGIS Spatial Analyst extension provides tools for spatial data analysis that apply statistical theory and techniques to the modeling of spatially referenced data.

A set of sample points representing changes in landscape, population, or environment can be used to visualize the continuity and variability of observed data across a surface through the use of interpolation tools. These changes can be extrapolated across the geographic space. The morphology and characteristics of these changes can be described. The ability to create surfaces from sample data makes interpolation both powerful and useful.

6.1. Interpolation methods

To create a surface grid in ArcGIS, the Spatial Analyst extension employs one of several interpolation tools. Interpolation is a procedure used to predict the values of cells at locations that lack sampled points. It is based on the principle of spatial autocorrelation or spatial dependence, which measures degree of relationship/dependence between near and distant objects.

Spatial autocorrelation determines if values are interrelated. If values are interrelated, it then determines if there is a spatial pattern. This correlation is used to measure:

- Similarity of objects within an area.
- The degree to which a spatial phenomenon is correlated to itself in space.
- The level of interdependence between the variables.
- Nature and strength of interdependence.

References [34,35] may be consulted for detailed information.

6.2. GIS maps of Iran

GIS maps make it easier to investigate and evaluate radiation in various locations and different months.

As solar data was not available for all the potential sites, interpolation was used to estimate the potential solar radiation in these locations.

In this work, thirteen GIS maps of monthly and annual total global horizontal irradiation were prepared for Iran which is presented in (Figs. 3–5). The contours have a scale of 1:10,000,000.

The values of horizontal radiation (GHR) from January to December are presented in Figs. 3–4. Fig. 5 shows Iran's annual average of total monthly radiation.

In GIS maps, solar radiation intensities are marked by colors. Thus, locations with better conditions are marked by colors nearer to the red color. As locations move toward low radiation levels, the marking color turns toward green.

According to the GIS maps shown in Figs. 3–4, the general increasing trend in the amount of radiation is visible as we move from north to south. The reason is that the latitude decreases along this direction and we get closer to the earth's equator. Northern Iran has the lowest radiation levels due to its higher latitude and greater cloudiness in most months of the year. Western regions exhibit lower levels of solar radiation than the southern and eastern parts due to their relatively higher altitude, the Zagros Mountain Range, and some mountains scattered in the region. As for seasonal changes, Mediterranean winds and clouds cause solar radiation received to be lower in autumn and winter than in spring and summer. Mediterranean winds often cause significant precipitation in western Iran to fall during cold seasons; hence, the lower radiation level in cold seasons than in warm seasons in the western parts. Southern and eastern regions of Iran receive much more radiation than other regions. As a

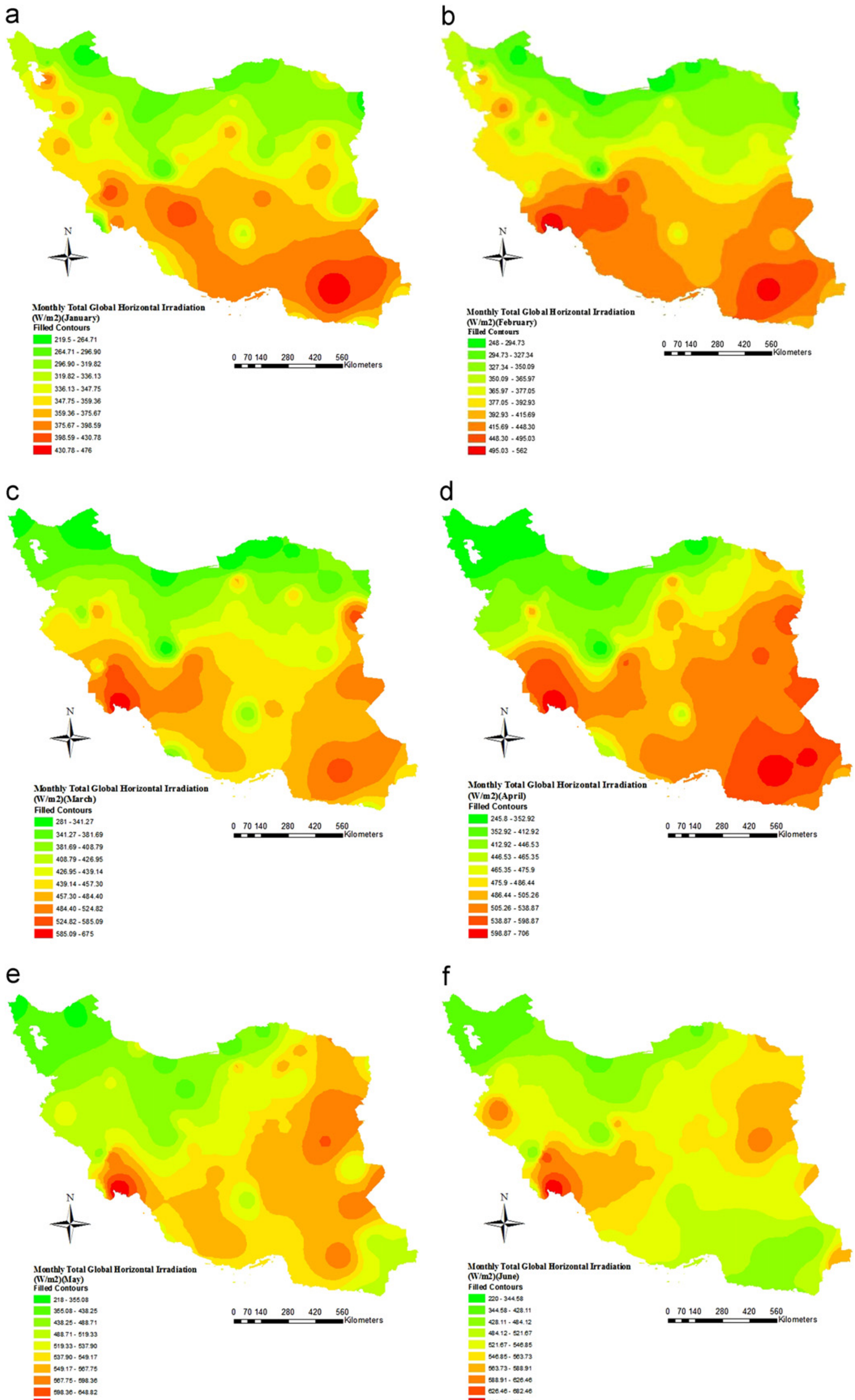

Fig. 3. Monthly average radiation on horizontal surface in (a) January, (b) February, (c) March, (d) April, (e) May, (f) June.

result, using such solar systems as solar heating, photovoltaic, etc. will be more economical in these regions. Based on GIS maps, the highest solar radiation received in these regions occurs in April.

In southwestern Iran and in Khuzestan Province, solar radiation is higher than in other regions in most months, with January receiving the lowest amount. Eastern Iran, especially Southern

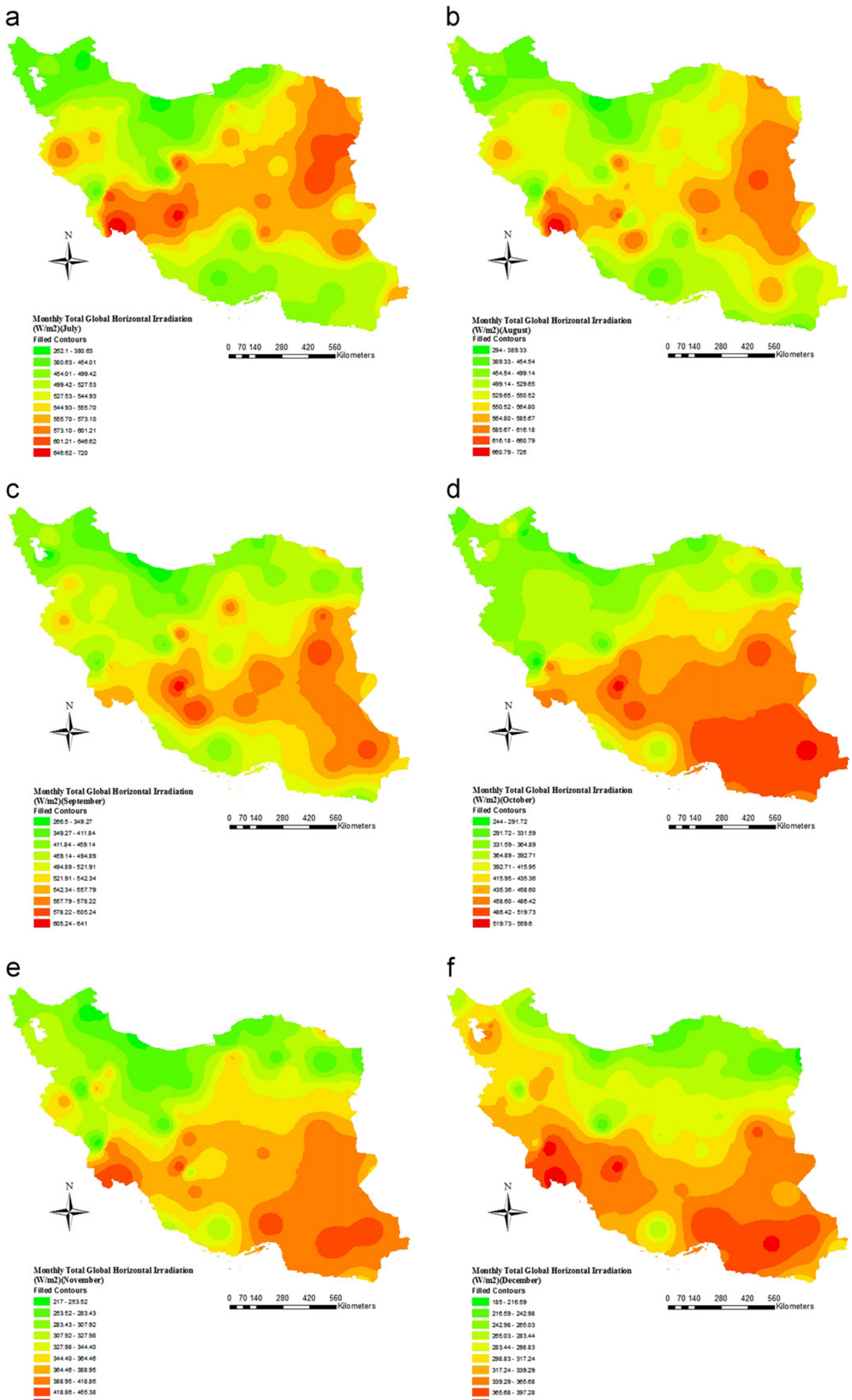

Fig. 4. Monthly average radiation on horizontal surface in (a) July, (b) August, (c) September, (d) October, e) November, (f) December.

Khorasan Province and the southern regions in Khorasan Razavi Province, receives considerable amounts of solar radiation due to the aridity (the Lut Desert) and lack of clouds in the region; hence, the high quantity of sunshine hours in these parts. Sistan and Baluchistan Province is located in southeastern Iran whose solar radiation is fair in cold months but lower in the warm months of

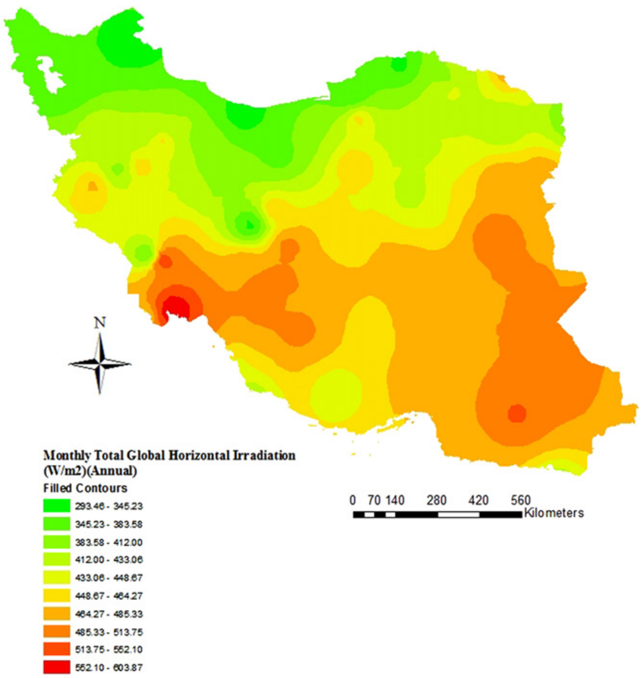

Fig. 5. Annual average of total radiation on a horizontal surface.

the year due to Sistan's 120-day winds which are a consequence of Indian monsoons reaching Iran through Afghanistan. These dust winds, blowing in warm seasons, have a great impact on the atmospheric conditions in Sistan and Baluchistan Province. The reduced amount of solar radiation is due to the reduced number of clear days that are normally the direct result of haze and dusty air in the region.

Based on the GIS maps prepared for the various months of the year, Iran's southern coastal areas receive lower quantities of solar radiation in the summer than in other seasons; its maximum value has been recorded in the month of April. This is while maximum solar radiation in many countries occurs in the summer. This is due to the high temperature and humidity in southern coastal areas. The same situation with maximum solar radiation in April and reduced solar radiation in the summer is observed in the United Arab Emirates, located in the southern coasts of the Persian Gulf [32].

ArcGIS that uses the effects of such other factors as distance from cities, roads, etc. can be exploited to identify the proper sites that receive good amounts of solar radiation. As SUNA has already considered these factors in installing its meteorological sites, ArcGIS in this study is just applied for interpolating data from the 63 sites mentioned.

7. Conclusion

In this study, the potential sites for exploiting solar energy were investigated using data from 63 stations across Iran. The values for maximum, minimum, and average annual horizontal radiation were obtained for each station. Moreover, monthly and annual clearness indices and annual average sunshine hours were obtained for the same stations. The data were used to develop both the annual average horizontal radiation map and GIS maps of horizontal radiation (GHR) over the 12 months of the year. According to the GIS maps, Iran's central and southern regions, except for the southern coastal areas, were found to be better sites in terms of the horizontal radiation received and their greater potentials for solar energy facilities. Among the mentioned regions, Southern Khorasan and Khuzestan provinces received significantly higher amounts of solar radiation, indicating that they can well be recommended as more economical and more promising sites for installing solar facilities. Furthermore, April was found to be the month with the greatest amount of solar radiation, regardless of site location. Finally, the recorded annual average values of horizontal radiation at Delgan, Mahshahr, Shushtar, Abadeh, and Fadashk stations were higher than 500 W/m^2, showing their potential for photovoltaic applications that makes them recommendable for further study.

Acknowledgments

The authors would like to thank the Ministry of Energy, Iran, especially the Renewable Energies Organization of Iran (SUNA), and Isfahan University of Technology for their support.

References

[1] Bagheri N, Moghaddam S, Mousavi M, Nasiri M, Moallemi EA, Yousefdehi H. Wind energy status of Iran: evaluating Iran's technological capability in manufacturing wind turbines. Renewable & Sustainable Energy Reviews 2011;14:4200–11.
[2] Mostafaeipour A, Sedaghat A, Dehghan-Niri AA, Kalantar V. Wind energy feasibility study for city of Shahrbabak in Iran. Renewable & Sustainable Energy Reviews 2011;15:2545–56.
[3] Mazandarani A, Mahlia TMI, Chong WT, Moghavvemi M. A review on the pattern of electricity generation and emission in Iran from 1967 to 2008. Renewable & Sustainable Energy Reviews 2010;14:1814–29.
[4] Thirugnanasambandam M, Iniyan S, Goic R. A review of solar thermal technologies. Journal of Renewable and Sustainable Energy 2010;14:312–22.
[5] Tsoutsos T, Frantzeskaki N, Gekas V. Environmental impacts from the solar energy technologies. Energy Policy 2005;33:289–96.
[6] 〈www.eia.doe.gov〉; May 2002.
[7] Parker L, Blodgett J. Greenhouse gas emission: conflicting situations, conflicting perspectives congressional research service. Library of congress; 2005.
[8] Mostafaeipour A. Feasibility study of harnessing wind energy for turbine installation in province of Yazd in Iran. Renewable & Sustainable Energy Reviews 2010;14:93–111.
[9] Chegaar M, Chibani A. Global solar radiation estimation in Algeria. Energy Conversion and Management 2001;42:967–73.
[10] Sabziparavar AA, Shetaee H. Estimation of global solar radiation in arid and semi-arid climates of east and west Iran. Energy 2007;32:649–55.
[11] Jacovides CP, Tymviosa FS, Assimakopoulosc VD, Kaltsounidesa NA. Comparative study of various correlations in estimating hourly diffuse fraction of global solar radiation. Renewable Energy 2006;31:2492–504.
[12] Wu G, Liu Y, Wang T. Methods and strategy for modeling daily global solar radiation with measured meteorological data—a case study in Nanchang station China. Energy Conversion and Management 2007;48:2447–52.
[13] Sen Z. Simple nonlinear solar irradiation estimation model. Renewable Energy 2007;32:342–50.
[14] Bulut H, Buyukalaca O. Simple model for the generation of daily global solar radiation data in Turkey. Applied Energy 2007;84:477–91.
[15] Paltridge GW, Proctor D. Monthly mean solar radiation statistics for Australia. Solar Energy 1976;18:235–43.
[16] Fadare DA. Modelling of solar energy potential in Nigeria using an artificial neural network model. Applied Energy 2009;86:1410–22.
[17] Bakirci K. Models of solar radiation with hours of bright sunshine: a review. Renewable & Sustainable Energy Reviews 2009;13:2580–8.
[18] Gastli A, Charabi Y. Solar electricity prospects in Oman using GIS-based solar radiation maps. Renewable & Sustainable Energy Reviews 2010;14:790–7.
[19] Kelley LC, Gilbertson E, Sheikh A, Eppinger SD, Dubowsky S. on the feasibility of solar-powered irrigation. Renewable & Sustainable Energy Reviews 2010;14:2669–82.
[20] Rehman S. Solar radiation over Saudi Arabia and comparisons with empirical models. Energy 1998;23:1077–82.
[21] Al-Ayed MS, AI-Dhafiri AM, Bin Mahfoodh M. Global, direct and diffuse solar irradiance in Riyadh. Saudi Arabia - Renewable Energy 1998;14:249–54.
[22] Benghanem M, Joraid AA. A multiple correlation between different solar parameters in Medina. Saudi Arabia - Renewable Energy 2007;32:2424–35.
[23] Sorapipatana C. An assessment of solar energy potential in Kampuchea. Renewable & Sustainable Energy Reviews 2010;14:2174–8.
[24] Daneshyar M. Solar radiation statistics for Iran. Solar Energy 1978;21:345–9.
[25] Jafarpur K, Yaghoubi MA. Solar radiation for Shiraz Iran. Solar & Wind Technology 1989;6:177–9.
[26] Samimi J. Estimation of height-dependent solar irradiation and application to the solar climate of Iran. Solar Energy 1994;52:401–9.

[27] Meinel AB, Meinel MP. Applied solar energy. New York: Addison Wesley; 1977.
[28] Yaghoubi MA, Sabazevari A. Further data on solar radiation in Shiraz Iran. Renewable Energy 1996;7:393–9.
[29] Sabziparvar AA. General formula for estimation of monthly mean global solar radiation in different climates on the south and north coasts of Iran. International Journal of Photoenergy 2007;32:649–55.
[30] Iran meteorological organization, 〈http://www.weather.ir/〉.
[31] Renewable energies organization of Iran, 〈www.suna.org.ir〉.
[32] Chaar LE, Lamont LA. Global solar radiation: multiple on-site assessments in Abu Dhabi. UAE Renewable Energy 2010;35:1596–601.
[33] Duffie JA, Beckman WA. Solar engineering of thermal processes. 2nd ed. New York: John Wiley and Sons; 1991.
[34] 〈gis.tulaliptribes-nsn.gov/Home/About/GISCenter.aspx/〉.
[35] 〈www.esri.com/news/arcuser/0704/files/interpolating.pdf〉.